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Lumped parameters multi-fidelity digital twins for prognostics of electromechanical actuators

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Abstract. The growing affirmation of on-board systems based on all-electric secondary power sources is causing a progressive diffusion of electromechanical actuators (EMA) in aerospace applications. As a result, novel prognostic and diagnostic approaches are becoming a critical tool for detecting fault propagation early, preventing EMA performance deterioration, and ensuring acceptable levels of safety and reliability of the system. These approaches often require the development of various types of multiple numerical models capable of simulating the performance of the EMA with different levels of fidelity. In previous publications, the authors already proposed a high-fidelity multi-domain numerical model (HF), capable of accounting for a wide range of physical phenomena and progressive failures in the EMA, and a low-fidelity digital twin (LF). The LF is directly derived from the HF one by reducing the system degrees of freedom, simplifying the EMA control logic, eliminating the static inverter model and the three-phase commutation logic. In this work, the authors propose a new EMA digital twin, called Enhanced Low Fidelity (ELF), that, while still belonging to the simplified types, has particular characteristics that place it at an intermediate level of detail and accuracy between the HF and LF models. While maintaining a low computational cost, the ELF model keeps the original architecture of the three-phase motor and the multidomain approach typical of HF. The comparison of the preliminary results shows a satisfactory consistency between the experimental equipment and the numerical models.

1. Introduction

In recent years, new alternatives to electrohydraulic actuators (EHA) are being investigated for primary and secondary flight actuations. Electrohydraulic actuators have been the main type of secondary power actuation in aviation since the adoption of servo-assisted commands in the 1950s given the high performances and reliability [1]. In the most basic form, an EHA is an hydraulic piston with two chambers; the pressure differential is what allows the movement of the piston which is connected to the element that has to be actuated. An EHA needs an high pressure system in order to save space, as actuation force is proportional to the area of the actuating piston and to the pressure differential on the two faces; since space is usually a constraint on aircrafts, the only viable alternative to increase the force output is to increase the pressure differential across the two faces of the piston. Thus, it can be explained why EHA for aerospace uses usually operate at very high pressure. As explained, the EHA needs a support system composed of pumps, tubes and control circuits. In high power applications, such as on

big passenger aircrafts, it is still convenient to have a dedicated high pressure hydraulic system, as it is the most power-dense (in terms both of volume ans mass) solution.

A more recent development of EHA is the electro-hydrostatic actuator (EHSA) [2], which is an all-in-one system. The main difference between a traditional EHA and EHSA is the localized production of high-pressure fluid inside the actuator assembly itself. The main advantage over traditional EHA is the reduced complexity of the system, even including redundancies, and reduced weight since there is no reinforced hydraulic lines carrying high pressure fluid along the aircraft, since in EHA generation and usage of the high-pressure fluid is not in the same location.

On the other hand, on UAVs or other less power-demanding applications, other solutions might prove lighter and simpler, in particular electro-mechanical actuators (EMAs). Rather than using hydraulics, EMAs relies on powerful electric motors to directly actuate the element of interest (flight control surfaces, primary or secondary). The simplest EMA has 4 elements: an electric motor, gearing to increase torque, ballscrew to convert rotation to linear motion, and a control system. They are also interesting for aviation in general given the shift towards the All Electric/More Electric design paradigm [3]. In general EMAs are widely adopted in industrial applications given the high simplicity of the system, but are not yet widely adopted on large aircraft for several reasons, including high weight and critical failure modes.

Regarding failure modes, one of the most common (and critical) is jamming [4], i.e. a failure condition where the ballscrew stops in a particular position and is unable to move. It is a very dangerous condition in aerospace applications since it can lead to flight surfaces remaining stuck in random positions and thus creating dangerous imbalances.

In order to mitigate this condition, prognostics can be used to monitor the system health status and evaluate continuously the probability of a failure, including jamming [5]. One way to do so is using an accurate model of the EMA system, to generate data representative of the real actuation system that can be used to obtain health indicators correlated to the health status of the system [6], as it is generally done in prognostics and health management (PHM) framework [7].

In this context, it becomes useful to have accurate models of the EMA system to be investigated. However, said high fidelity (HF) models are usually computationally expensive and thus not suited for real time monitoring; thus, lower fidelity model are useful to have a real-time digital twin of the EMA system which can be used for prognostics as monitoring model (i.e. a model that ca be used to compare the real responses of the system to those given by the monitoring model).

This paper tries to bridge the gap between HF modeling (as in [8]) and Low Fidelity (LF) modeling (as in [9]) of an EMA for flight controls. As previously explained, semplifications are needed to reduce the complexity of the LF model to make it suitable for real-time monitoring. However, an excessive simplification of the model reduces adherence to physics and can fail to represent phenomena of interest. Thus, the Enhanced Low Fidelity (ELF) reduces some of the strong simplifying assumptions made by the authors in previous works. ELF response will then be tested against the HF model to validate performances and accuracy.

2. ELF Model

The ELF model, as previously stated, has several key differences with both the HF and LF model, even tough the overall structure is very similar to the HF model, as visible in Fig. 1.

The main difference with LF model is the use of a 3-phase architecture rather than an equivalent-single phase approach (Fig. 2). Maintaining such an architecture allows the modeling, in a direct way, of some faults of interest, e.g. partial phase shorts, without losing physical meaning as done in the LF model where different shape functions have been defined.

In order to reduce numerical complexity, the electrical driver has been strongly simplified and abstracted (Fig. 3). Since the switching MOSFETs are easily the most demanding element to

run (given the high frequency of the PWM), the elimination of said elements and substitution with a simplified model has greatly increased simulation speed.
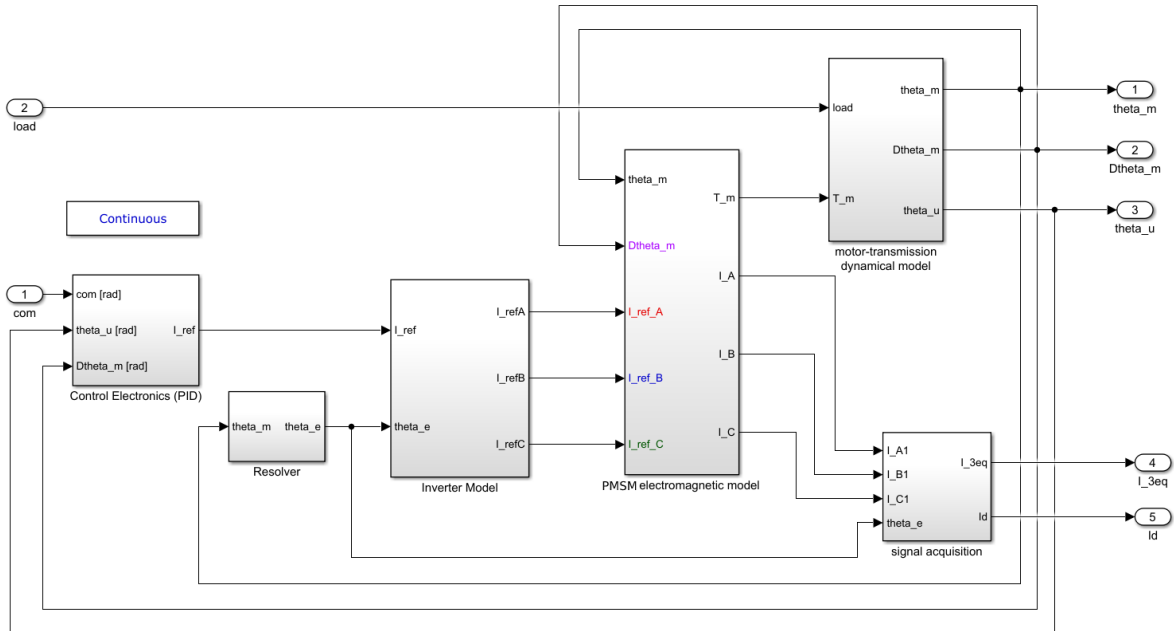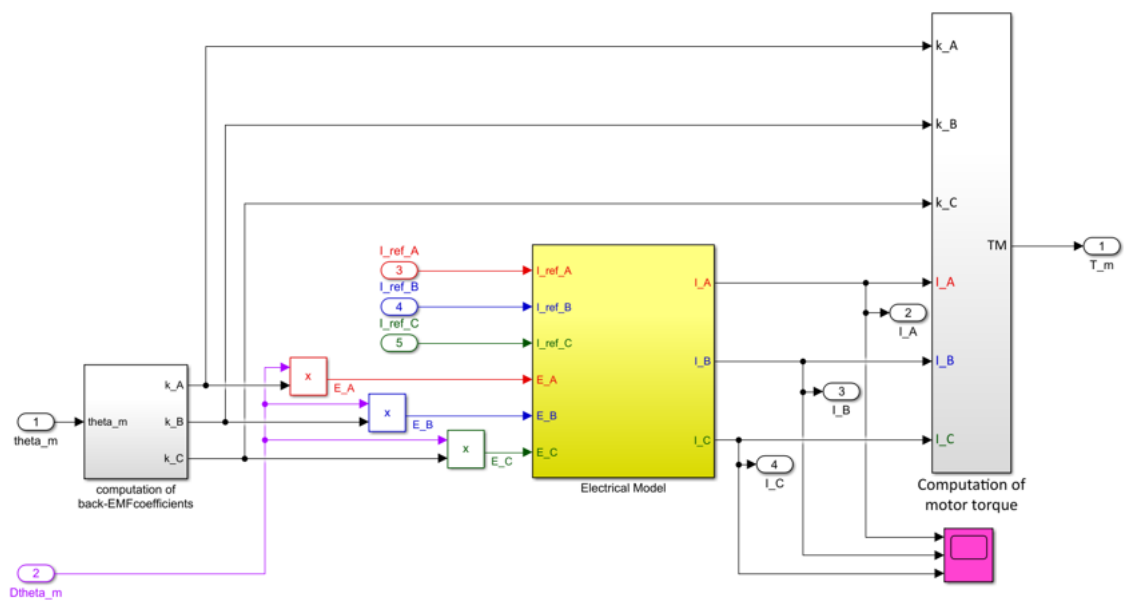

Figure 1: ELF model overview.

Figure 2: ELF 'electromagnetic model' overview.

In short, the following equation is used to evaluate the active current on a single phase:

$$\frac{\pm V_{DC} - e_j}{R \cdot n_j} = \pm i_j^{MAX}, \quad j = a, b, c \tag{1}$$
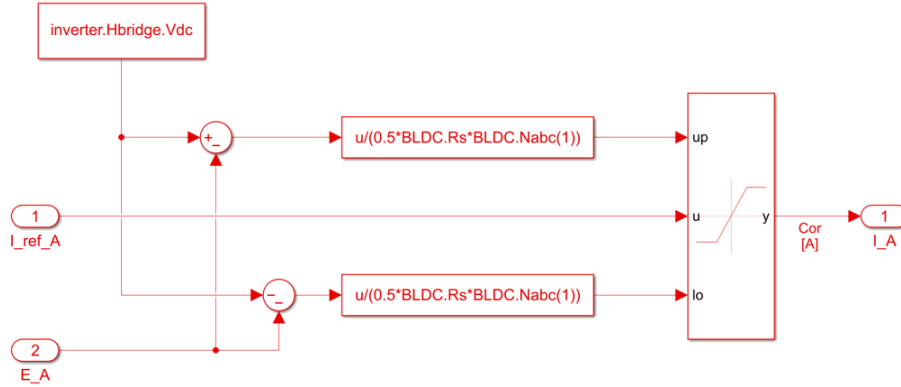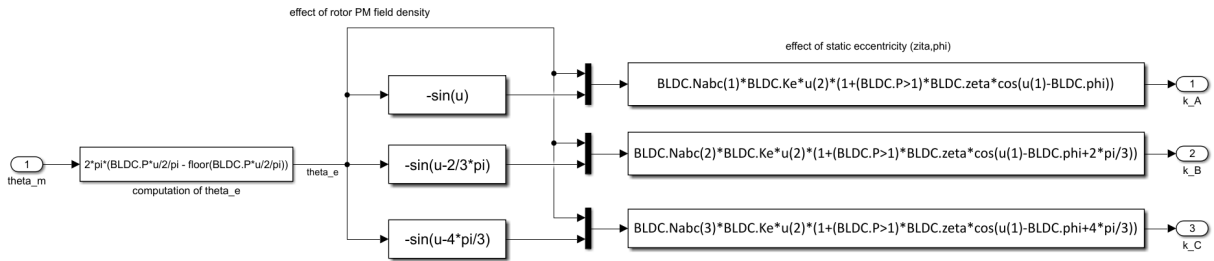
Figure 3: Simplified driver for ELF model (phase A).

Figure 4: Back-EMF calculation.

where V_{DC} is the supply voltage, e_j is the back-EMF voltage, n_j is the percentage of turns in short in the given phase and R is the nominal resistance. In this case, the output current is limited by the previous equation, while inside the bounds there is a direct proportionality between the requested current (I_{ref_A} in this case) and the actual current provided by the inverter I_A.

In Fig. 3, the nominal resistance is defined as $0.5 \cdot R_s$ where R_s is the series line resistance which is an easier parameter to acquire on a real system.

Another difference is in the calculation of the back-EMF for the model, as visible in Fig. 4. Firstly, the electrical angle is calculated from the mechanical angle, then the following equation is used (for phase A) to evaluate the back-EMF coefficient:

$$k_a(\vartheta_e) = -N_a \cdot K_e \cdot sin(\vartheta_e)[1 + p \cdot \zeta \cdot cos(\vartheta_e - \phi)] \tag{2}$$

where k_a is the back-EMF coefficient of phase A for a given electrical position ϑ_e, N_a is the percentage of non-shorted turns in phase A, p is the number of pole pairs (greater than 1), ζ is the static eccentricity and ϕ is the eccentricity phase. Similar equations are valid for phases B and C and can be deducted from Fig.4.

3. Accuracy and performances comparison
In this section, several variables of interest will be compared between the original high fidelity (HF) model and the ELF model presented in this paper.

3.1. Accuracy
The variables monitored are motor angular position, motor speed and equivalent single-phase current, which is simply the quadrature current used to drive the permanent magnet motor; it

is derived in the classical way using the Clarke and Park transformations.

In total, 3 different simulations have been conducted using sinusoidal and step with ramp commands. Simulation details are shown in Table 1, using the following parameters: A is amplitude (or initial amplitude in case of the chirp command), f is frequency and t_0 is the application time.

Trial	A [rad]	f [rad/s]	t_0 [s]
SIN	0.1	2π	0
SIN4	0.5	10π	0
STEP-RAMP	0.1/-0.1 rad/s	-	0.01/1.25

Table 1: Simulation parameters overview

(a) STEP-RAMP position and velocity
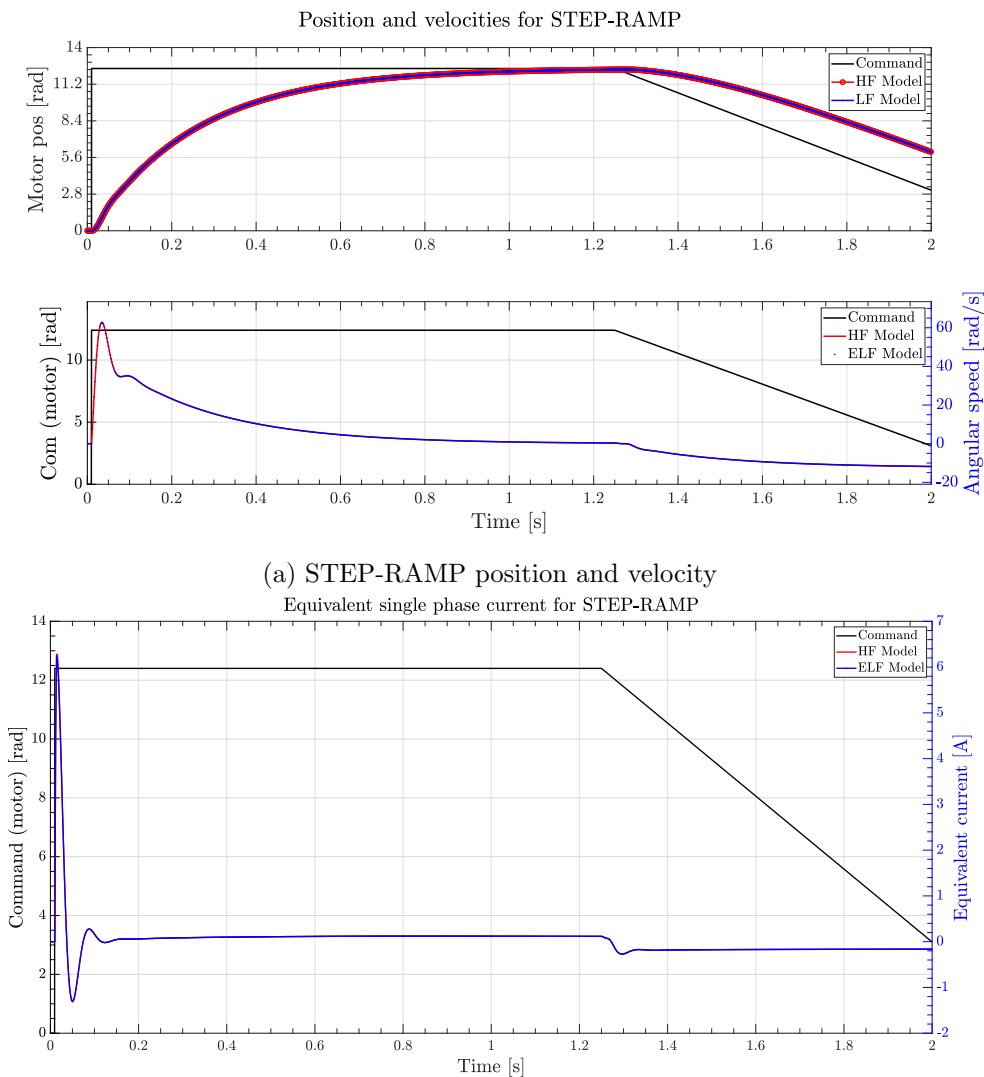
(b) STEP-RAMP equivalent current

Figure 5: STEP-RAMP simulation

In Figures 5, 6, 7 the motor position and speed, the imposed command and equivalent single phase current are shown. It can be seen how the model is very accurate and reproduce almost exactly the behavior of the HF reference model. However, as visible in Fig.7a and 7b, in saturation conditions, a very significant discrepancy between the two models can be observed.

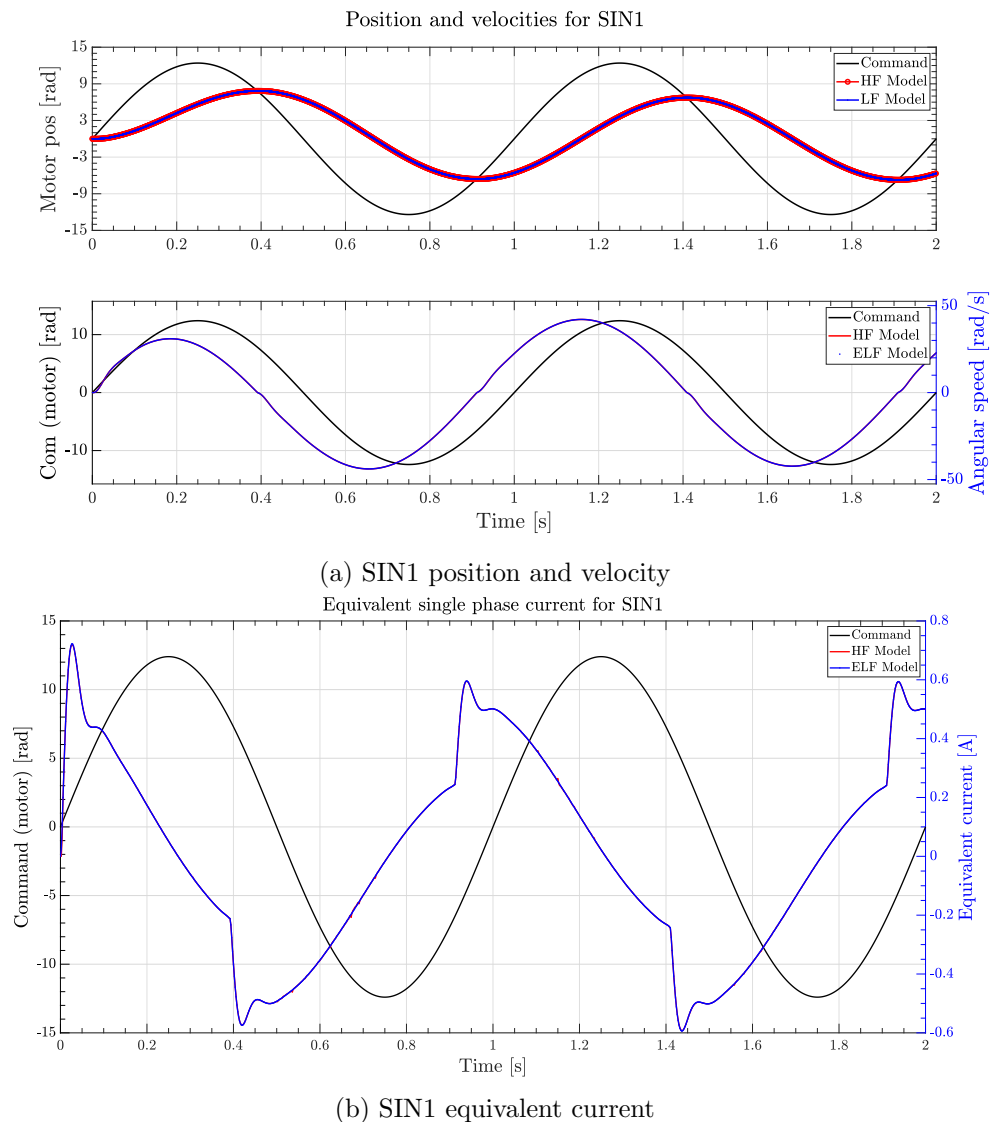(a) SIN1 position and velocity

(b) SIN1 equivalent current

Figure 6: SIN1 simulation

In saturation conditions a very large difference with respect to the HF model can be observed in Fig.7b. This is caused by the different modeling of the electrical part of the model. In fact, the ELF model computes the three phase currents independently, which is an accurate approximation until one (or more) phases are in saturation conditions.

In the HF model, when a phase is in saturation conditions, the other phases are also affected, and thus a more realistic behavior can be observed in Fig.7a, where the HF model reproduce a sinusoidal behavior (for position), while the velocity becomes a triangular wave since the motor runs at maximum speed in both directions; on the other hand, the ELF model express a more complex (and unrealistic) behavior.

(a) SIN4 position and velocity
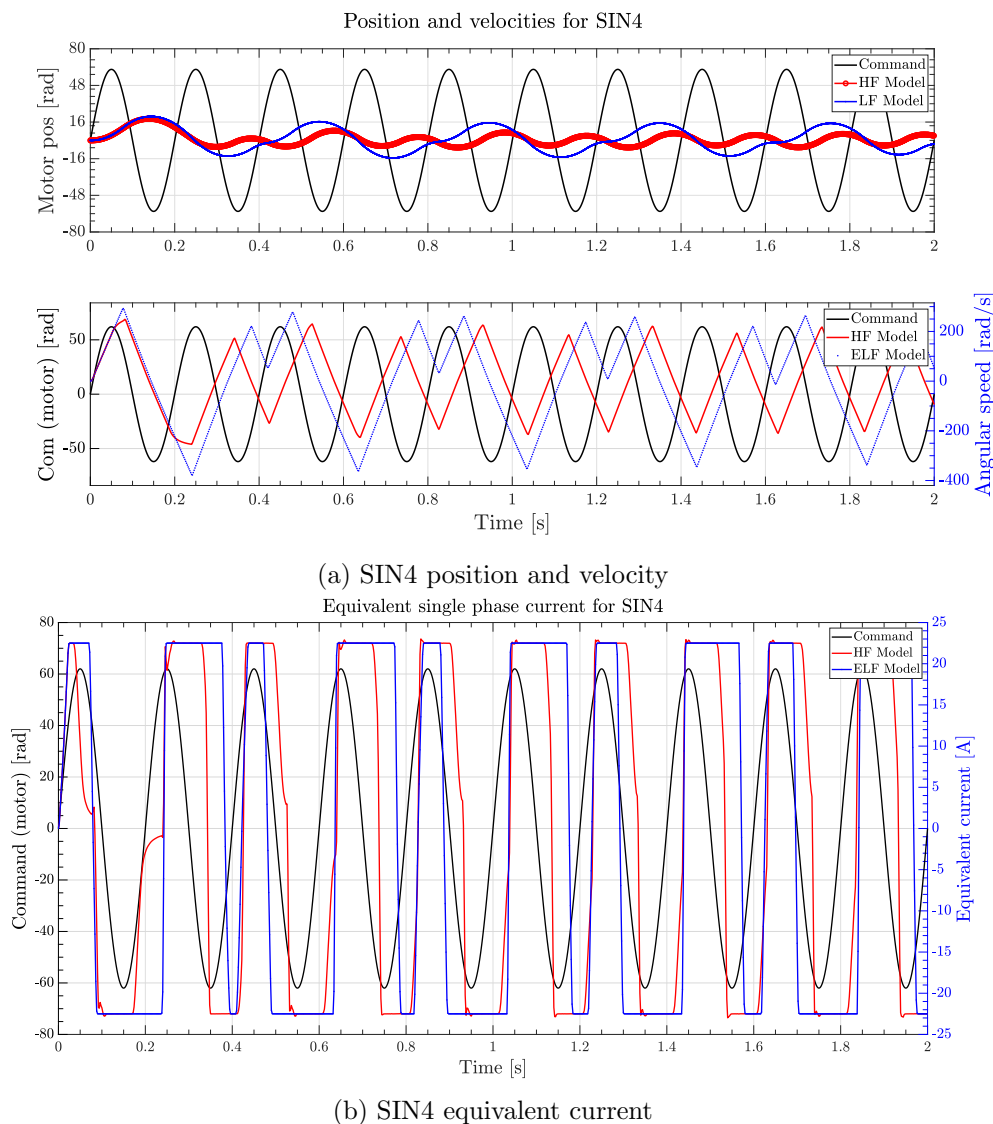

(b) SIN4 equivalent current

Figure 7: SIN4 simulation

In Fig.7b, a marked aperiodicity of the quadrature current is observable on the ELF model, while the HF model, after an initial setting period, tend to stabilize on a periodic pattern.

3.2. Performances comparison

The main advantage of using a lower fidelity model is the reduction in computation time. All the value reported below were obtained using Matlab R2021B on an XPS-7590 with an Intel i7-9750H. The models were tested using both normal mode and accelerator mode.

The average run-time for the simulations presented above is of 1.8 s using the ELF model in normal mode and 0.8 s in accelerator mode. On the other hand, the HF model average run-time is of ca. 180 s in normal mode and of 17.5 s in accelerator mode.

In particular, the main time-consuming subsystem is the 'Electrical model' inside the 'PMSM electromagnetic model', which takes 0.53 s for the ELF in accelerator mode, 1.82 s for the ELF in normal mode, 6.63 s for the HF in accelerator mode and 97.6 s for the HF using normal mode.

The other resource-intensive subsystem is the 'Inverter model', using ¡1 ms for the ELF in

accelerator, 16 ms for the ELF in normal mode, 2.8 s for HF in accelerator and finally 10.3 s for HF in normal mode. It has to be noted that for the HF in normal mode a significant contribution is given by the detailed PID controller using 17.5 s.

It is evident how using a simplified model lead to much faster run-times which are in the order of about 100x using normal mode and about 20x in accelerator mode.

4. Conclusions

In this paper, a new lower fidelity (ELF) model of an electromechanical actuator for possible near real-time applications has been presented, tested for a number of actuation commands.

The main simplifications lies in a more simple modeling of the inverter and of the electromagnetic interaction of the PMSM electromagnetic model, where the phase voltages are not explicitly calculated and the phase currents are evaluated independently from each other.

From preliminary simulations, it can be observed that the ELF model tracks very well the high fidelity reference model in most conditions where no phase saturations is present, as such cases will invalidate the assumption of phase independence.

The main advantage of using a lower fidelity model is the reduction in computation complexity and thus simulation time; it has been shown that the time savings are of at least an order of magnitude with respect to the HF model, and can be further increased when using the Simulink accelerator mode. Having simulation rates of less than 1s/s enable the use of the ELF as monitor model in real-time monitoring strategies.

However, the model will need to be updated to include an improved logic for phase saturation and a robust handling routine, as to have a more representative reproduction of the real model, since this limitation is quite severe and impedes the as-is deployment of the ELF model in a real life condition.

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